Sedimentology (1993) **40**, 1091–1111

Obstacle marks produced by flow around stranded ice blocks during a glacier outburst flood (jökulhlaup) in west Greenland

ANDREW J. RUSSELL*

Department of Geography, University of Aberdeen, Elphinstone Road, Old Aberdeen AB9 2UF, UK

ABSTRACT

The effects of glacier ice block grounding on the morphology and sedimentology of proglacial fluvial outwash were examined during a glacier outburst flood or jökulhlaup, near Søndre Strømfjord, west Greenland. Observations made during and after the 1987 jökulhlaup both on the surface of an ice contact delta and within a confined valley sandur plain provided information about the formation of ice block obstacle marks and the significance of these bedforms for sandur morphology and sedimentology. Flow directions determined from obstacle mark morphology have been used successfully to chart flow direction changes on the falling limb of the jökulhlaup. Maximum flow depths for scour around stranded ice blocks may be given by 0·5–0·9 times the diameter of the ice block, as estimated from the depth of scour, the height of the obstacle shadow or the extent of ice block meltout sediments. Minimum flow depths can be represented by the height of the obstacle shadow above the mean bed level. The internal composition of the shadow indicates the ability of the flow to transport various sizes of material into the lee of obstacles. Ice block obstacle marks within the distal portion of the sandur initiated waning stage channel change. Proximal and lateral erosion around stranded ice blocks extended downstream from the ice block, forming chute channels which then captured waning stage flows, resulting in significant bar incision with associated deposition of lobate or deltaic deposits. It is suggested that ice block obstacle marks are important in terms of channel morphology, channel morphological change and their usefulness as palaeohydrological indicators.

INTRODUCTION

This paper examines the effect of glacier ice block grounding on the morphology and sedimentology of proglacial fluvial outwash during a glacier outburst flood or jökulhlaup in west Greenland. Hollows, pits, or 'comet' marks attributed to fluid flow around grounded ice blocks have been documented by Collinson (1971), Fahnestock & Bradley (1973), Gustavson (1974) and Scholz *et al.* (1988). Despite the common occurrence of ice block obstacle marks on proximal proglacial outwash, few studies have considered processes involved in their formation or their detailed sedimentary characteristics. Indeed, the full significance of ice block grounding and obstacle mark formation on sandur morphology and stratigraphy remains to be investigated (Elfström, 1987). Observations made during and after a jökulhlaup in west Greenland provided information about the formation of ice block obstacle marks and their significance for sandur morphology and sedimentology.

STUDY AREA

The river channel under investigation flows along the northern margin of the Russell Glacier 25–30 km north-east of Søndre Strømfjord, west Greenland (Fig. 1). Ice block grounding was observed on both an ice contact delta and a confined valley sandur plain (Fig. 1). Periodic jökulhlaups result from the sudden subglacial drainage of a large ice-dammed lake on the northern flank of the Russell Glacier (Sugden *et al.*,

---

* Present address: School of Geography, Kingston University, Penrhyn Road, Kingston Upon Thames, Surrey KT1 2EE, UK.

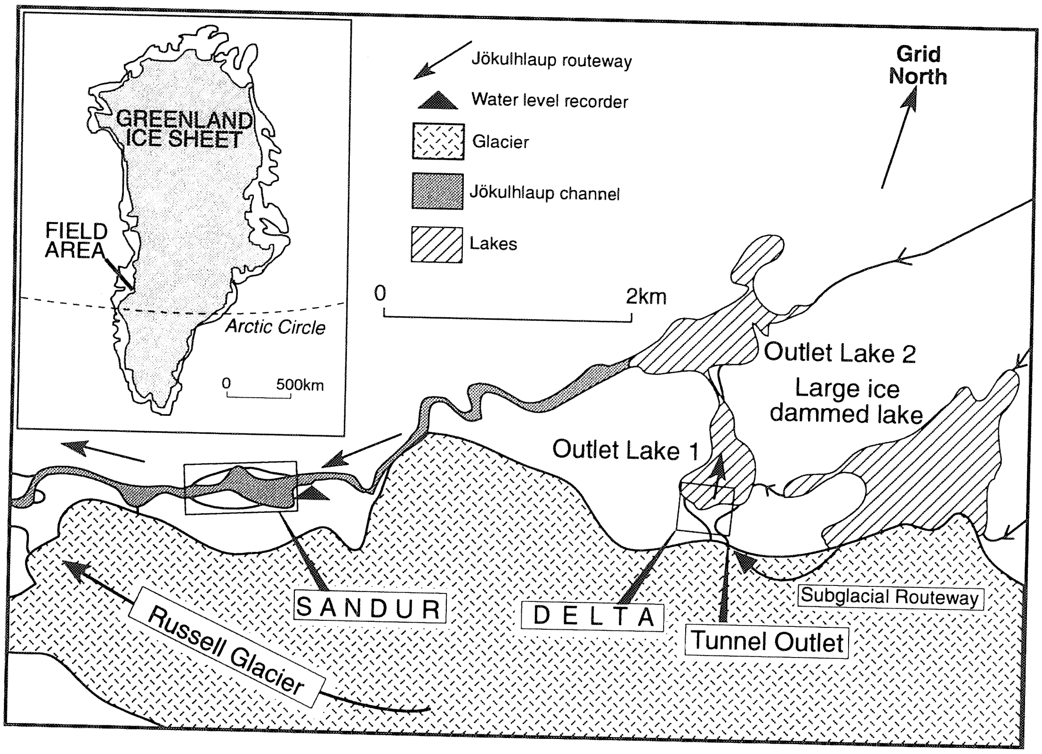


Fig. 1. Location map of the field area within Greenland and the field areas examined in detail.

1985; Gordon, 1986; Scholz *et al.*, 1988; Russell, 1989, 1991; Russell & de Jong, 1989; Fig. 1).

ICE BLOCK RELEASE DURING JÖKULHLAUPS

Jökulhlaups resulting from the sudden subglacial drainage of ice-dammed lakes are likely to contain large numbers of ice blocks derived from the ice-dammed lake basin, the collapse of subglacial tunnels, or from the undercutting of downstream glacier margins by direct fluvial activity. Indeed, large numbers of ice blocks scattered across alluvial reaches of the study channel during a jökulhlaup in 1984 were derived predominantly from the undercutting and collapse of glacier margins and front by fluvial activity (Sugden *et al.*, 1985).

The size of the ice blocks entrained and transported by jökulhlaups is related to the transport capacity and depth of flow. Jökulhlaup timing is also important in relation to seasonal ice margin position and ice margin stability. Ice blocks deposited during the waning flow stage will act as obstacles to the remaining flow.

FLOW AROUND OBSTACLES

Obstacle mark forming processes were examined by Sengupta (1966), Karcz (1968), Richardson (1968), Carstens & Sharma (1975) and Allen (1984). Obstacles such as ice blocks, boulders, bridge piers and other solid objects fixed within a river bed produce localized flow acceleration (Fig. 2). Carstens & Sharma (1975) suggest increases in bed shear stress of up to 12 times that of undisturbed flow. Secondary flow cells are produced as flow is deflected downwards and outwards from an obstacle in the form of a 'horseshoe' vortex (Fig. 2). Enhanced velocities immediately in front of and to the sides of an obstacle prevent the deposition of sediment and can carve out U-shaped scour marks (the open end of the U pointing downsteam; Fig. 3). Flow separation may produce a zone in the obstacle lee, where 'shadow' ridges may be deposited or preserved (Fig. 3).

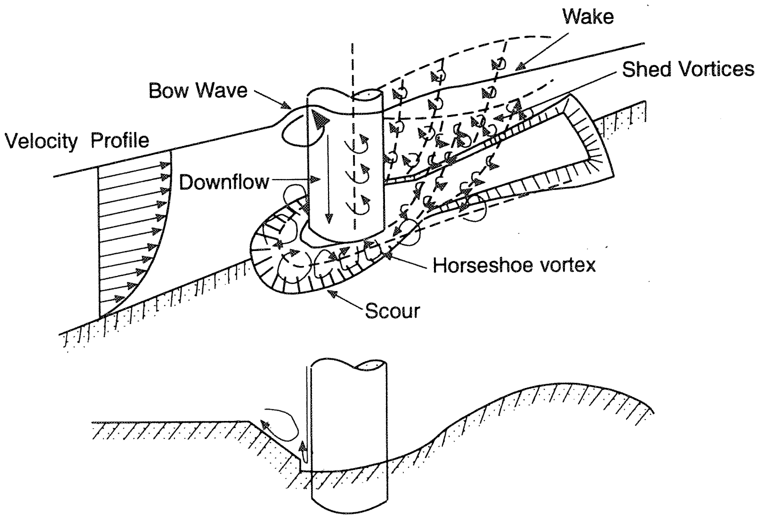


Fig. 2. Schematic diagram showing the patterns of flow acceleration around obstacles to flow such as bridge piers and ice blocks (after Bradley & McCutcheon, 1987). Note association of horseshoe vortices with proximal scour and of shed vortices with lee side deposition.

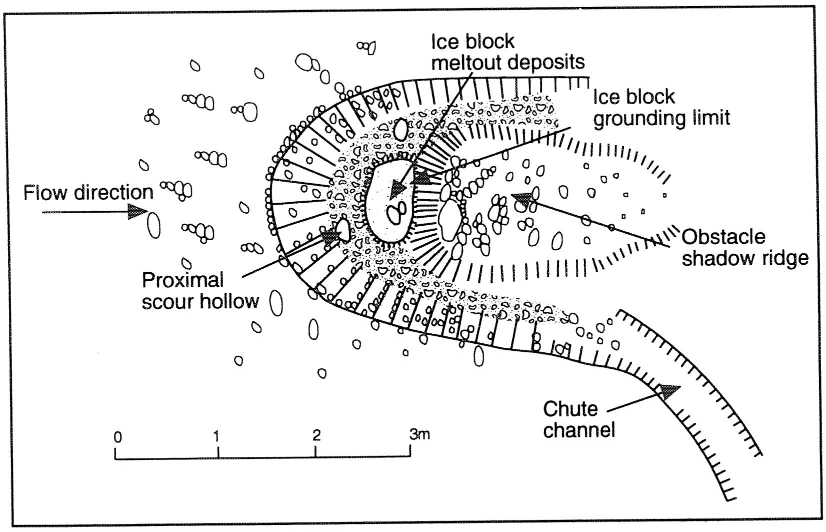


Fig. 3. Plan view morphology of a typical obstacle mark found on the sandur.

Major variables influencing the type of obstacle scour mark formed are outlined in Table 1. Some of these relationships are quantitative, such as the simple, experimentally derived, empirical relationships between the depths of scour, H_s, and the diameter of the obstacle, D, suggested by Larras (1963) and Breusers (1965) and outlined in Allen (1984). Karcz (1968), Richardson (1968) and Shen *et al.* (1969) related the depth of scour H_s to the obstacle Reynolds number determined from the mean flow velocity (U_{mean}),

Table 1. Relationships between obstacles, obstacle marks and flow conditions.

Reference	Relationship
Larras (1963)	$H_S = 1{\cdot}05D$
Breusers (1965)	$H_S = 1{\cdot}4D$
Shen *et al.* (1969)	$H_S = 0{\cdot}000223(U_{\mathrm{mean}}D/v)^{0{\cdot}619}$

H_S, depth of scour (m); U_{mean}, mean flow velocity; D, obstacle diameter (m); v, kinematic viscosity [dynamic viscosity (N s m^{-2})/fluid density (kg m^{-3})].

obstacle diameter (D) and the kinematic viscosity (v). As specific conditions under which these equations should be used are not defined, flows around bridge piers are regarded as similar to those around stranded ice blocks. The only variables which can be determined in both present river channels and the sedimentary record are: (i) exceptionally the dimensions of the ice block, (ii) the dimensions of the scour features, (iii) the sizes and sorting of sediment involved and possibly (iv) the gradient of the channel in which they lie. Any information concerning palaeoflow directions, depths, and sediment transport conditions which can be inferred from the simple relations in Table 1 may therefore be extremely valuable.

THE 1987 JÖKULHLAUP

Observed ice block grounding on the delta

Observations of the delta, between 16:00 and 17:00 hours on 18 July 1987, near the flood peak indicated flows emanating from a tunnel mouth at the head of a confined channel and spreading out over most of the delta surface (Fig. 4). The level of the outlet lake

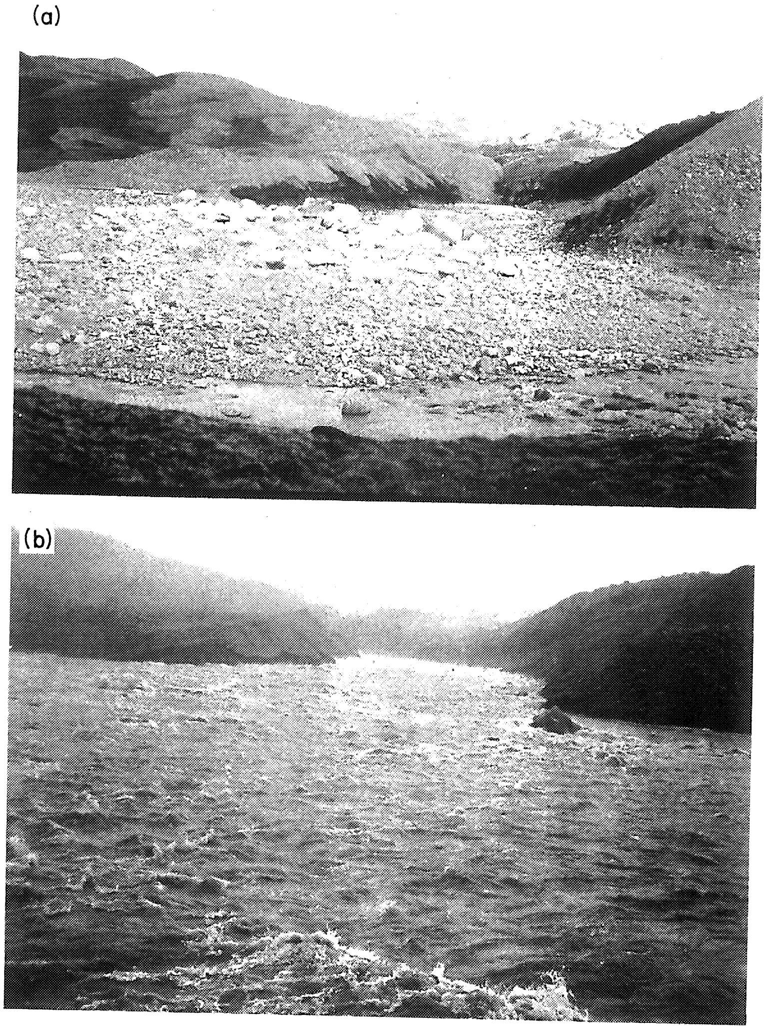


Fig. 4. (a) Ice blocks stranded across the jökulhlaup delta immediately after the 1987 jökulhlaup. Most ice blocks are deposited immediately in front of the subglacial tunnel outlet. (b) Peak 1987 jökulhlaup flows over the delta from the same view point as (a). Flows are directly towards the viewer. Note ice blocks grounding on the higher sections of the delta. Peak jökulhlaup discharge is 1300 m^3 s^{-1} at this site. The channel between the moraine ridges is c. 80 m wide.

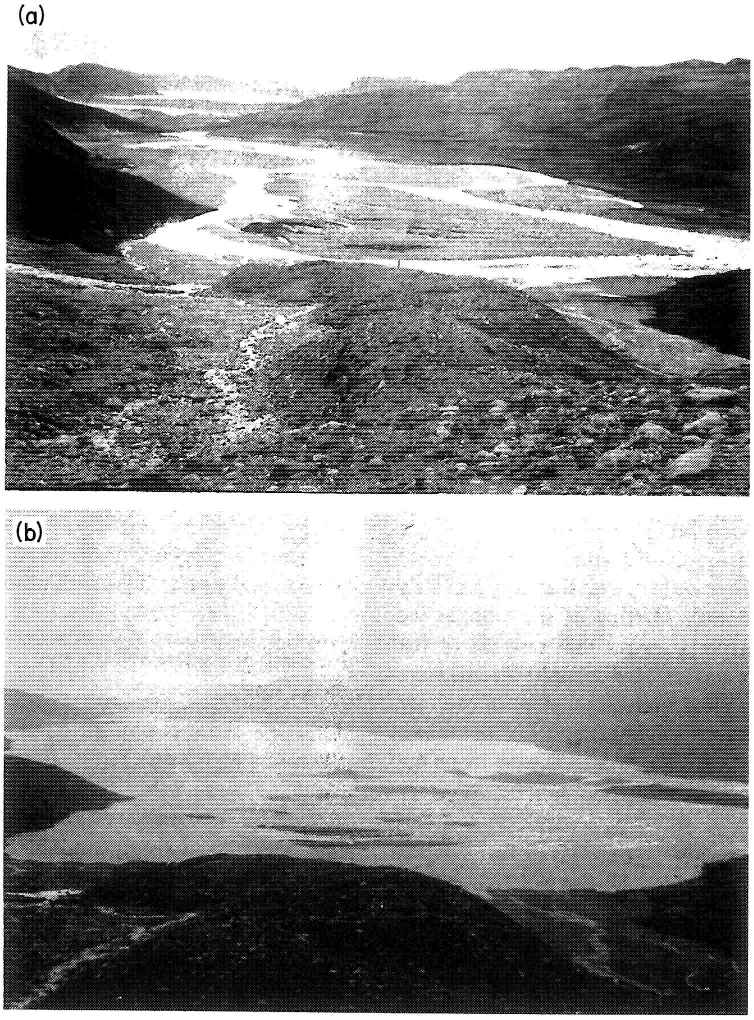


Fig. 5. (a) Sandur during 'normal' flows prior to the 1987 jökulhlaup. Sandur is 1 km in length and 500 m wide. Note figure on moraine ridge in foreground. (b) Sandur during peak 1987 jökulhlaup flows.

during the 1987 jökulhlaup was observed to be *c.* 5·5 m above normal. Only small clusters of coarse material could be seen above the peak water level. Numerous large ice blocks released from the area around the tunnel outlet travelled down the confined channel, grounding audibly on the proximal side of high relief areas of the delta where flows separated into two main channels (Fig. 4). Ice blocks were commonly grounded for a few minutes before rolling or floating away, with the processes being repeated several times. Grounding was accompanied by an audible increase in cobble/boulder movement. Many grounded ice blocks observed during peak flow conditions were found *in situ* several days after the event (Fig. 4a).

Observed ice block grounding on the sandur

During peak 1987 jökulhlaup flows, parts of the sandur were submerged to depths of up to 3–4 m (Fig. 5). Ice blocks began appearing in the river just before the flood peak at 16:00 hours on 18 July and during the waning stages of the flood (Fig. 6). The influx of ice blocks was due to undercutting and collapse of an ice cliff by flood waters 1 km upstream of the gauged

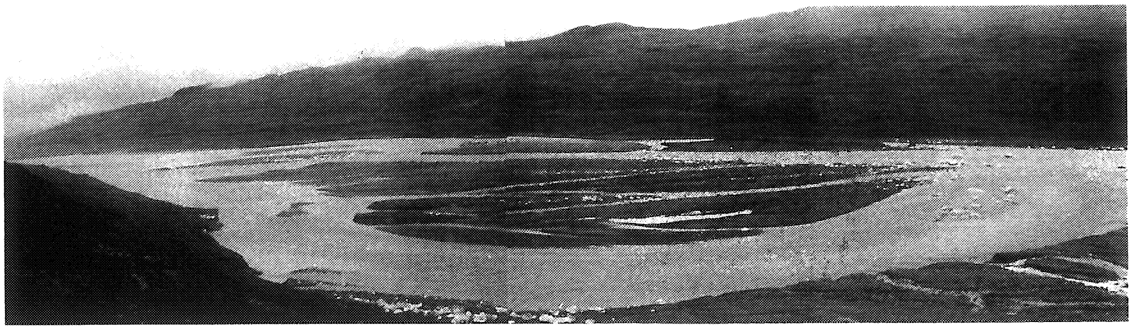


Fig. 6. Large numbers of ice blocks stranded over the sandur surface on the waning stage of the jökulhlaup.

reach (Fig. 6). The ice blocks were deposited on the relatively rapid, 6 h, waning stage of the flood (Fig. 7). Most blocks were deposited between 16:00 and 21:00 hours on 18 July before flow returned to normal by 06:00 hours the following day (19 July). Data concerning the measured and former original dimensions of ice blocks were collected on the 22 and 23 July (4 days after the flood). Melting of the smaller ice blocks prior to sampling meant that only 53 of the largest ice blocks and associated scour bedforms were considered. Former maximum dimensions of each ice block were derived from measurements of the maximum extent of a layer of debris released from the grounded ice block by melting. Some of the larger ice blocks (4 × 3 × 3 m in diameter) survived for 3–4 weeks, suggesting relatively low rates of melting. As it was thought likely that the nature of the substrate would be an important control on obstacle mark morphology, the following data were gathered. Of 53 ice block obstacle marks sampled, only seven were subjected to systematic sediment size analysis using a phi scale grid. Surface (armoured layer) and subsurface (subarmoured layer) sediment samples were taken at several locations proximally to distally through each feature. Only material larger than $-2{\cdot}5\ \phi$ (5·6 mm) was sampled, precluding direct comparison of percentile size and sorting data with other river channels.

Ice block grounding and channel morphological change on the sandur

Although channel pattern change as a result of the 1987 jökulhlaup was minimal, a large, distal, gravel bar was dissected (Fig. 8). This bar advanced by 60 m in a down sandur direction prior to waning stage erosional activity, splitting the bar into three fragments, separated by two semi-parallel erosional chute channels (Fig. 8). Concentration of waning stage flows around stranded ice blocks initiated localized scour, allowing chute channel development (Fig. 8b). Bar

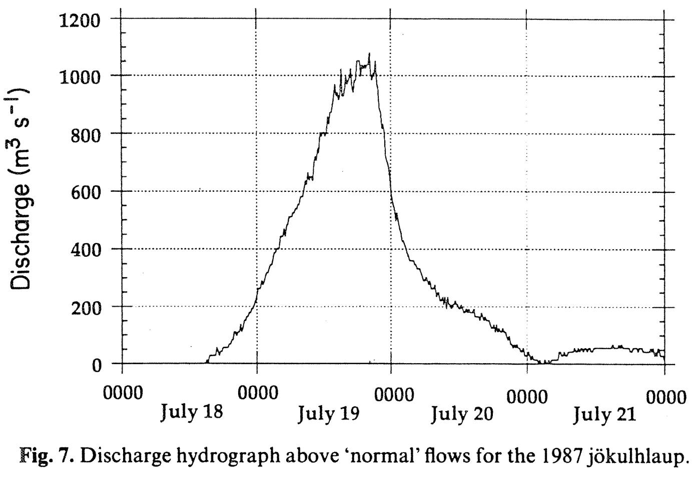


Fig. 7. Discharge hydrograph above 'normal' flows for the 1987 jökulhlaup.

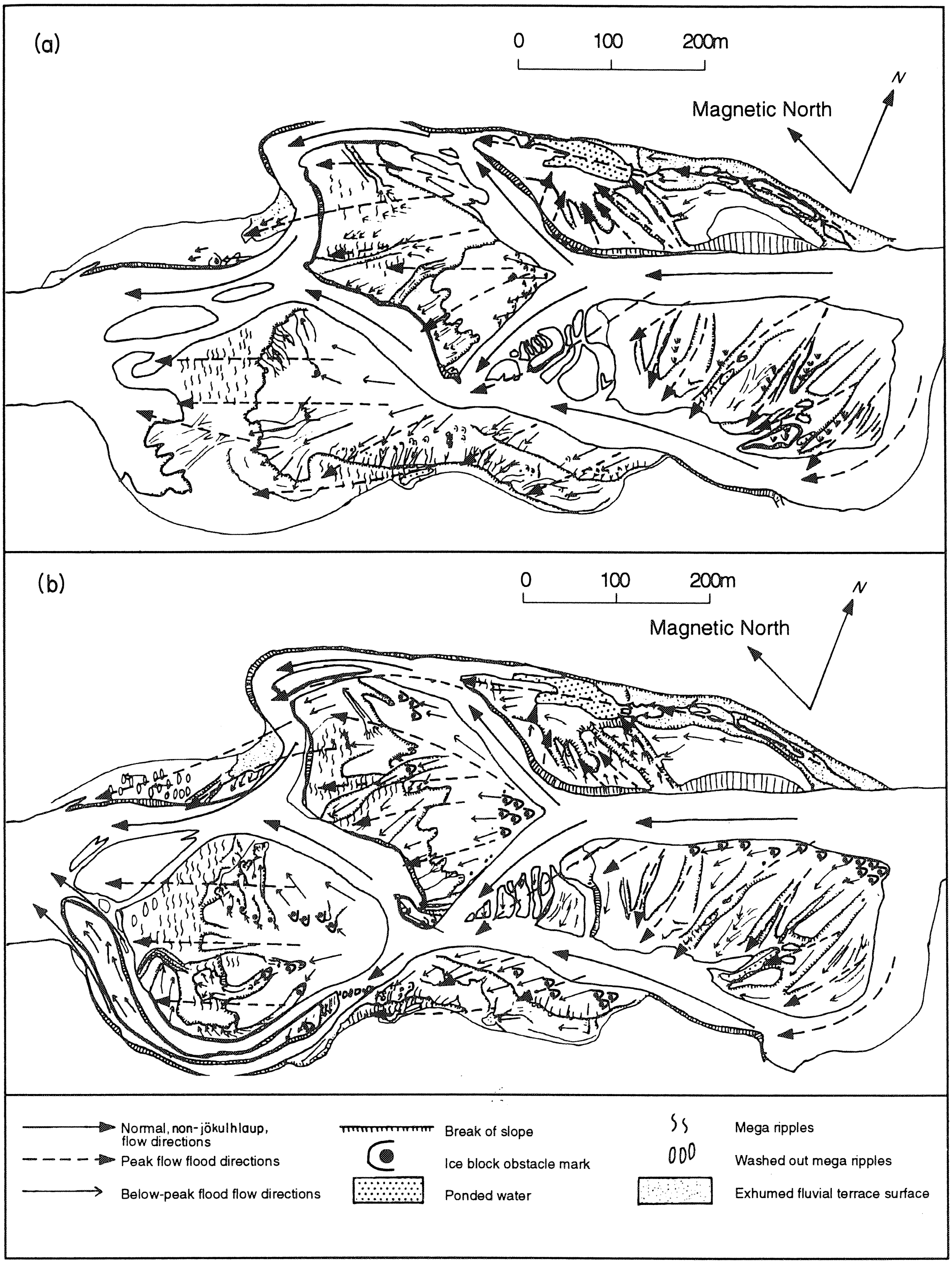


Fig. 8. (a) Pre-1987 jökulhlaup sandur morphology. (b) Post-1987 jökulhlaup sandur morphology.

dissection was observed at 21:00 hours on 18 July, i.e. when waning stage flows were of the order of 100 m^3s^{-1} (Fig. 7). Incision continued through the 1987 and early 1988 melt season until the channel achieved relative stability. Channel change on the sandur can therefore be divided into two categories: first, that resulting from rising stage depositional extension and aggradation of pre-existing bars; and second, that caused by waning stage erosional activity. Channel change was most marked on the southern side of the sandur in the form of bar extension. Ice block grounding was very effective in disrupting and reworking even the coarsest bar surfaces.

THE MORPHOLOGY OF THE ICE BLOCK SCOUR MARKS AND DISTRIBUTION OF ICE BLOCKS

The delta

Ice block obstacle marks observed before the 1987 jökulhlaup were all obliterated and replaced by new, larger, obstacle marks (Figs 4a, 9 and 10a). After the jökulhlaup, both 'clean' ice blocks and blocks containing black, clast-rich, sediment of possible basal ice origin were observed where they had grounded (Fig. 10b). The former melted out leaving a thin layer of sediment of 'porridgy' appearance, whilst the latter left 0·5–1 m high piles of very poorly sorted sediment ranging from silt to cobble sizes (Fig. 10c). Similar sediment-rich diamicton blocks have been identified within Quaternary outwash sediments (Krainer & Poscher, 1990). The diameter of the meltout deposits appeared to conform with the former diameter of the ice blocks (Maizels, 1977). After the jökulhlaup, ice blocks were found sitting within large hollows with maximum depths of 2–3 m. The ice blocks appear to have become progressively imbricated as proximal hollows were scoured out. Areas to the lee of the grounded blocks contained an accumulation of generally finer grained, better sorted, cobble–gravel sized material whilst the bottom and sides of the hollows contained coarser grained, clast supported boulders

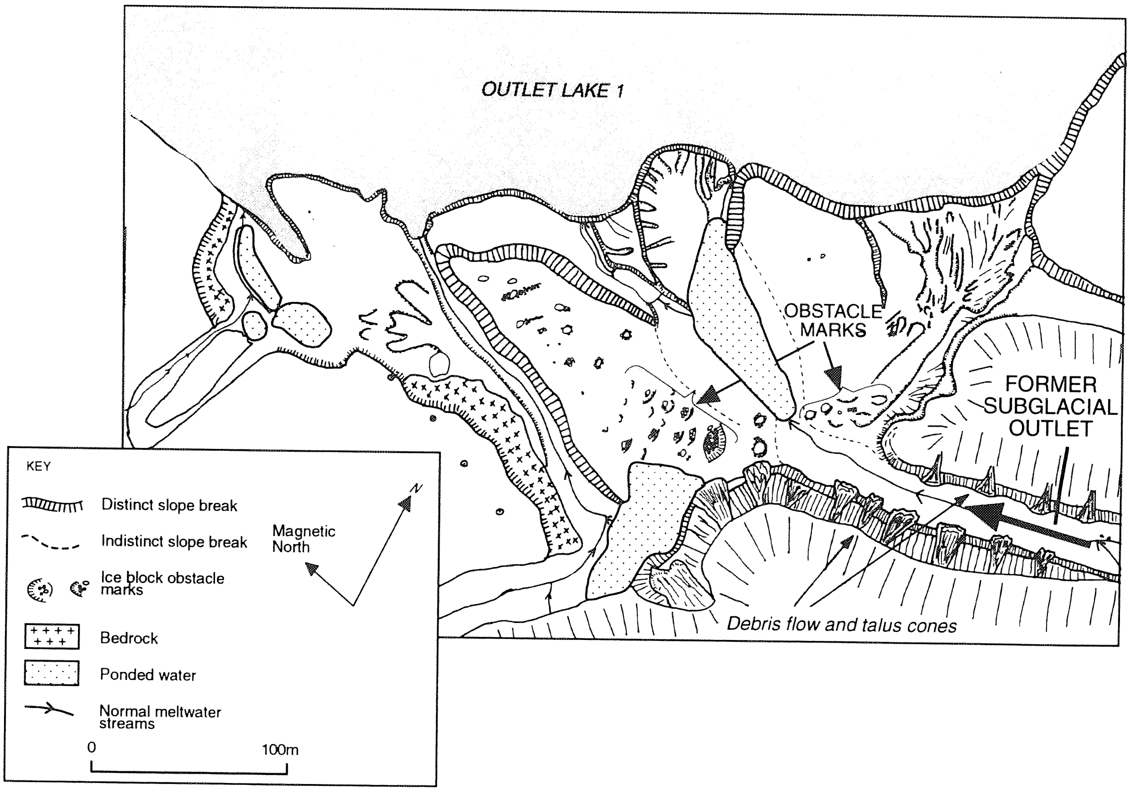


Fig. 9. Post-1987 jökulhlaup geomorphological map of the delta.

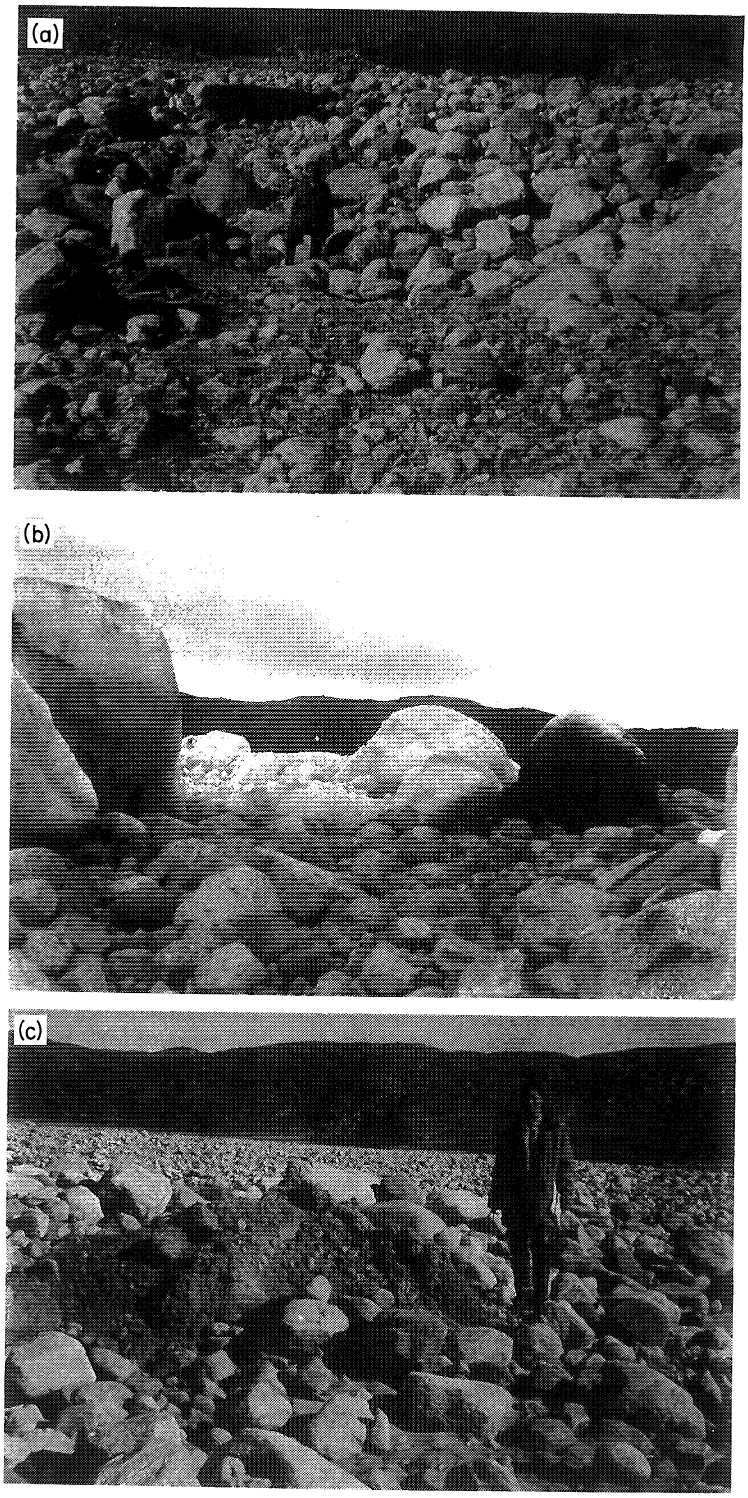


Fig. 10. (a) A large ice block grounding hollow on the main delta surface. Total relief amplitude of this hollow is 3 m. Note finer cobble sized material on the obstacle shadow ridge at the top right of the photograph. (b) Clean and dirty ice blocks on the delta surface. Ice axe and rucksack are 0·75 m in height. (c) Poorly sorted ice block meltout deposit 3 weeks after the jökulhlaup.

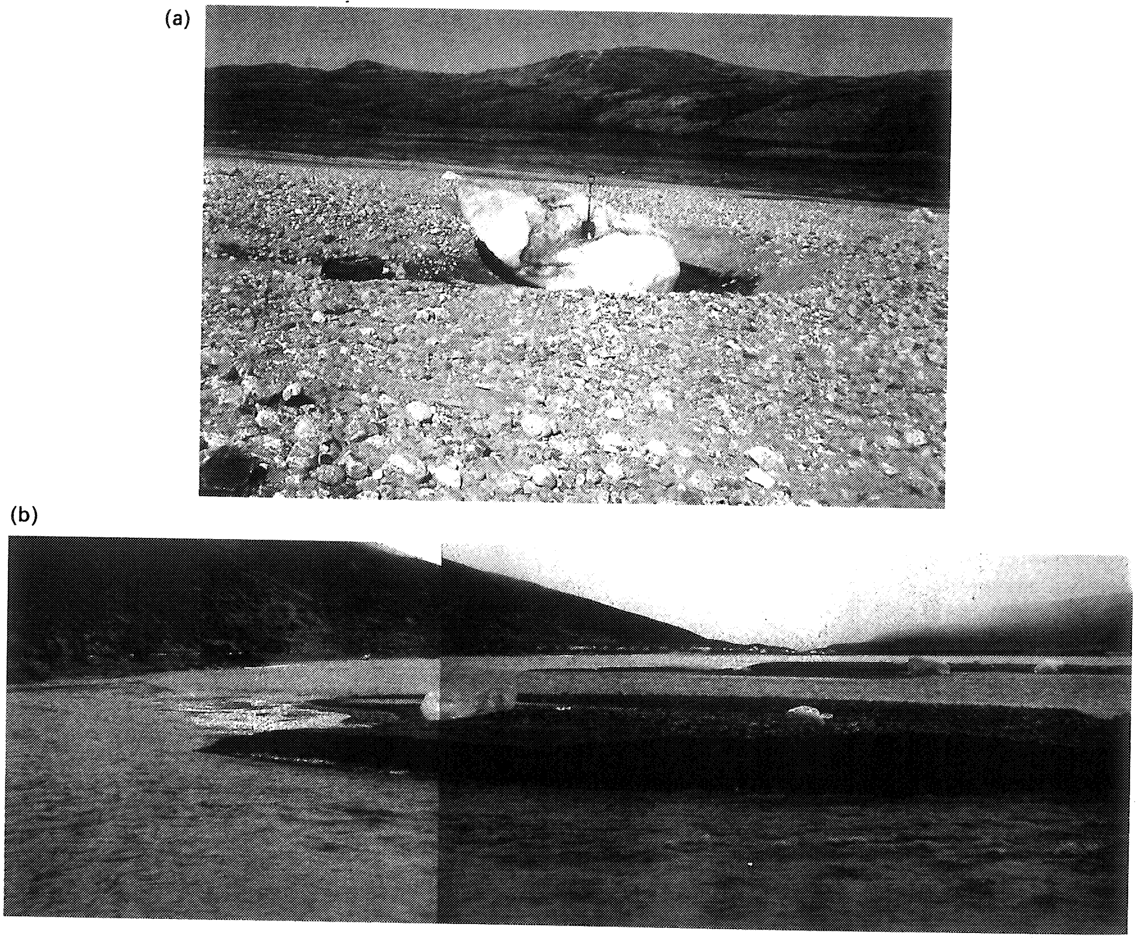


Fig. 11. (a) Ice block obstacle mark on the sandur. Note scour proximal and lateral to the ice block and deposition in the obstacle lee. The ice block has also been progressively imbricated. Shovel is 1 m in length. (b) Waning stage chute channel development as a result of scour around grounded ice block obstacles. Note maximum jökulhlaup stage marked by wash limits at the left of the photograph. Bar edge in foreground is *c.* 12 m in length.

(Fig. 10a). Proximal scour and lee side deposition resulted in a maximum relief amplitude of 4 m.

The sandur

The ice block scour marks found on the sandur had two main components: a scour hollow on the upstream and lateral margins, occasionally extending great distances downstream from the ice block (5 m maximum); and a 'shadow' in the form of a ridge or pile of sediment found in the ice block lee (Figs 3 and 11a). Sediment shadows rise up to 1·5 m above the mean sandur bed level (Figs 3 and 11a). When coupled with maximum stoss side scour depths of up to 1·25 m, total ice block obstacle mark relief amplitude reached a maximum of 2·75 m (Fig. 12). As such, these features were as significant in terms of relief amplitude as other sedimentary structures (e.g. bars, dunes, megaripples and chute channels) found within this channel (Fig. 11b).

Scour around stranded ice blocks affected both local coarse sediment fraction sorting and size distributions. In most cases the shadow or pile of material was composed of the most poorly sorted surface and subsurface sediment. However, obstacle shadow material was still finer than found in the bottom of the proximal hollow, but similar in size to the upstream river bed. The coarsest material at the scour hollow

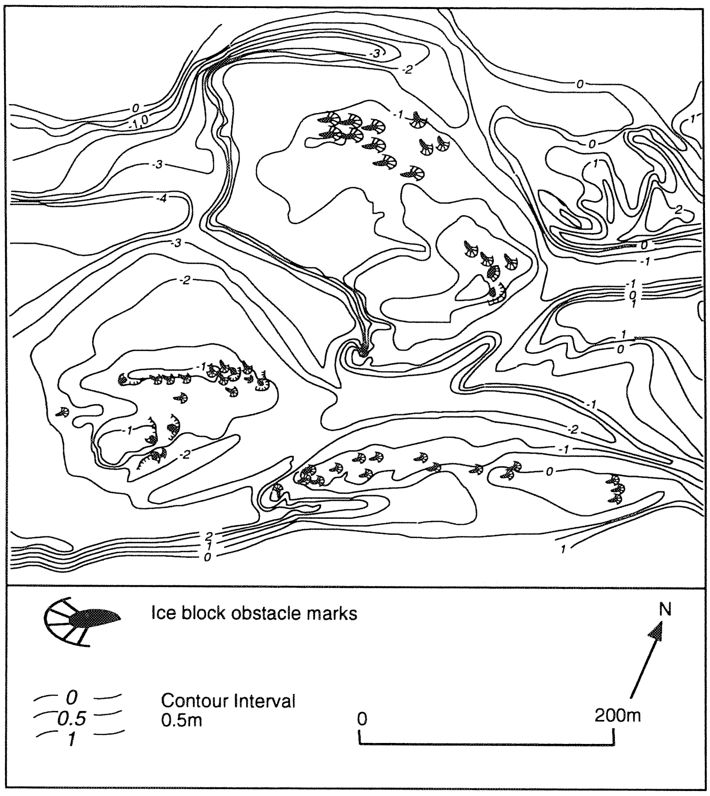


Fig. 12. Location of the largest ice block obstacle marks superimposed upon a 0·5 m interval contour map of the central part of sandur 1. Note that ice blocks have grounded on the crests of the bar surfaces.

bottom was left as a lag deposit after the removal of fines by winnowing (Fig. 13). For ice block obstacle marks developed within the coarsest undisturbed substrate, sorting was locally improved on the bottom of the hollow and within the shadow area.

Ice blocks were grounded, mostly along the edges of main channels and on the stoss sides of main bar units (Fig. 12). Owing to the positive buoyancy of ice blocks, higher areas of the channel constituted preferred grounding locations (Fig. 12). Coarse cobble–boulder sized material in the proximal portions of several bars 'captured' numerous large ice blocks (Fig. 12). Numerous small ice blocks, less than 1 m in diameter, were deposited during the rapid waning flood stage on reverse gradients of several bar surfaces (Figs 4, 11b and 12).

As ice block obstacle marks were found mainly on high relief bars during waning flood stages their preservation potential was relatively high. Thus, only an event of equal or greater magnitude will be able to modify or remove the structures from the highest bar areas. Ice block obstacle marks may thus enhance the record of floods by locally increasing the thickness of individual flood units by deposition in the lee of the ice block.

TESTS OF PUBLISHED RELATIONSHIPS CONCERNING THE EFFECTS OF OBSTACLES ON RIVER CHANNEL MORPHOLOGY

Previous analysis derived from field-work by Karcz (1968) and Allen (1984), and from theoretical and laboratory work by Richardson (1968) and Shen *et al.* (1969), suggested relationships between flow conditions, obstacle size, obstacle shape and obstacle morphology. Relationships concerning obstacles, obstacle marks, flow conditions and substrate characteristics are examined below for ice block obstacle marks on the sandur plain.

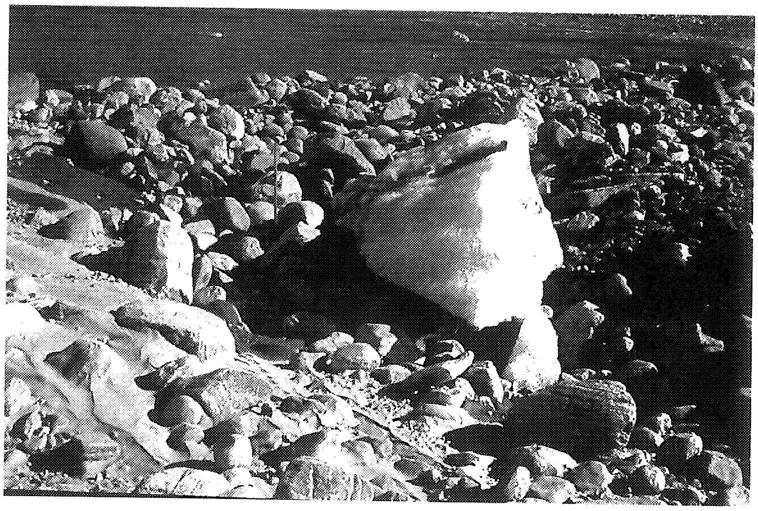


Fig. 13. An ice block grounded on the coarse grained head of a sandur bar. Flow is from left to right. Note proximal scour and distal deposition of finer grained gravels to the right of the ice block. Stick is 1 m in length. Proximal scour has left a coarse lag in the floor of the hollow.

Dependence of obstacle mark morphology on the erodibility of the substrate

Karcz (1968) and Allen (1984) suggested that obstacle mark morphology may be influenced by the erodibility of the river bed, such that an easily eroded substrate will result in greater depths of scour. Bar erodibility may depend upon the size and sorting of the substrate. Surface and subsurface grain size and sorting were determined for the Greenland obstacle marks, since bed armouring may produce differentially erodible surface and subsurface layers. The size of over 200 clasts (sampling surface and subsurface separately) within a 0·5 m grid provided D_{84}, D_{50} and D_{16} values, which were then used to calculate sediment sorting values. As scour depth around an obstacle depends both upon the erosive potential of the flow and upon the resistance of the bed to scour, a relationship between the size and sorting of sediment and obstacle mark erosional morphology might be expected. As no clear relationship exists between clast size alone and depth of scour (H_s; Fig. 14), the relationship between flow conditions and both substrate characteristics and scour depths is more complex.

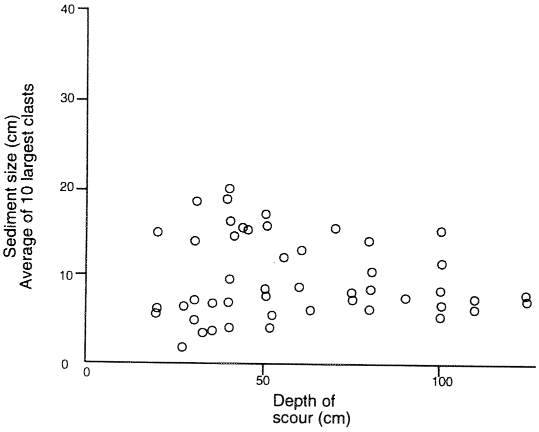


Fig. 14. Plot of particle size of bar surface sediment upstream of obstacle marks against depth of scour below mean bed level.

Size of the obstacle in relation to the flow depth

The depth of flow under which ice block obstacle marks are initiated may vary, depending upon ice block density. Ice block obstacles by their very nature provide flow depth information as ice block flotation occurs at maximum depths of 0·9 times the obstacle size (based on relative density of pure ice and water). Sediment-rich ice blocks as observed on the delta surface are likely to have a much higher density requiring greater water depths for flotation. Observed water depths when ice blocks were saltating along the river bed were only *c.* 0·5–0·6 times the obstacle diameter (Fig. 15). This suggests that obstacle marks were produced in water depths of less than 0·5–0·6

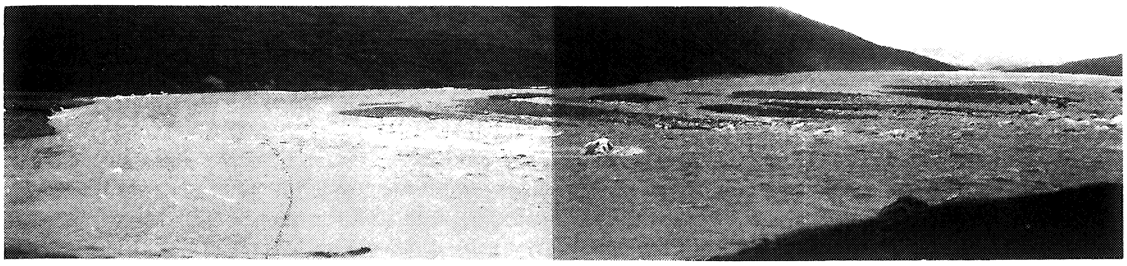


Fig. 15. Ice blocks rolling along the proximal portion of the sandur during the 1987 jökulhlaup. Note development of horseshoe vortices on the proximal (right) side of the ice blocks 2–3 m in diameter.

times the obstacle diameter when ice block rolling ceased. Several ice blocks on the sandur slid along the bed without rotation prior to final grounding.

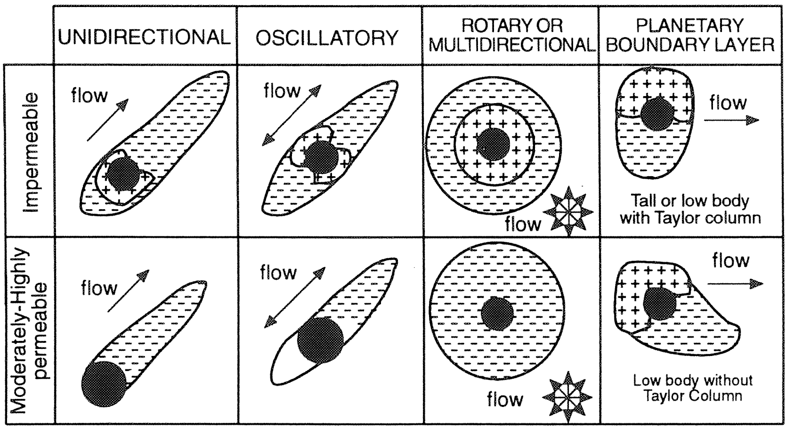
The morphology of the obstacle marks in relation to mean bed shear stress

Areas of non-erosion or deposition are characterized by negative bed shear stress whilst areas of non-deposition or erosion represent areas of increased bed shear stress (Carstens & Sharma, 1975; Allen, 1984; Fig. 16). Ice block obstacle marks found on the sandur commonly exhibited stoss side and occasional lateral scour (Figs 3, 13 and 17). Obstacle shadows were arranged either as downstream tapering ridged or mound-like forms transverse to the palaeoflow direction (Fig. 18; after Allen, 1984). A zone of finer grained surface sediment was seen, occasionally, upstream of the scour pit (Fig. 18).

There is general compatibility between the bedforms expected by the shear stress distributions suggested by Allen (1984) and the pattern of erosion and deposition found by Carstens & Sharma (1975), and the obstacle marks found on both the delta and the sandur (Figs 11, 17 and 18). Previous experimental studies used well sorted sand, much finer grained and better sorted than anything found within this study.

Relationship between depth of scour and the size and shape of the obstacle

Karcz (1968) indicates a relationship between the depth of scour, H_s, and the size of the obstacle, D, for smaller clast obstacles up to 0·3 m in diameter and for scour depths of up to 0·2 m. Allen (1984) provided two empirical equations after Larras (1963) and Breusers (1965) concerning relationships between scour depths and obstacle size (see Fig. 23). Data from ice block



+ Stress greater than average - Stress less than average

Fig. 16. The effects of obstacles to flow on mean bed shear stress (after Allen, 1984).

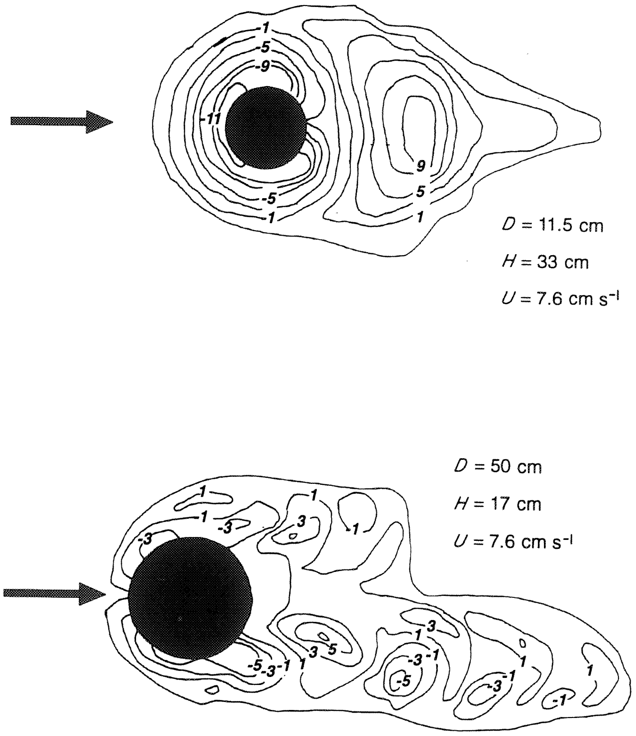


Fig. 17. Morphology of scour around an obstacle (after Carstens & Sharma, 1975). *D*, obstacle diameter; *H*, flow depth, *U*, flow velocity. Arrow shows flow direction.

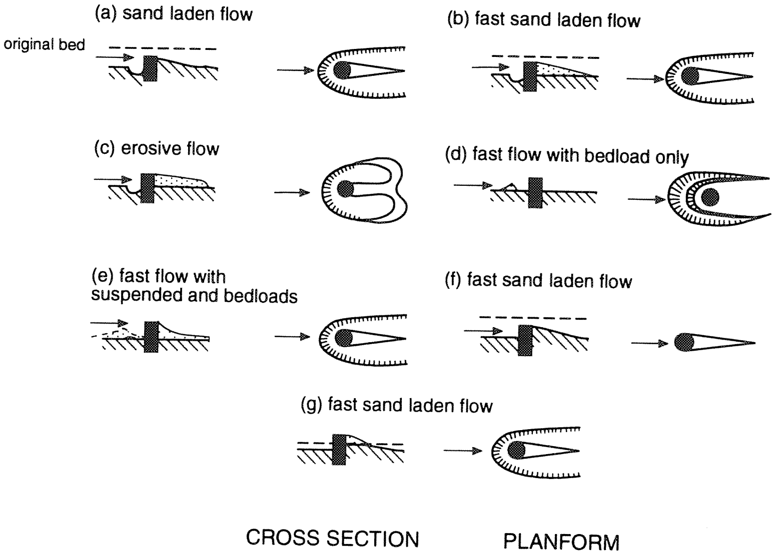


Fig. 18. A range of crescentic hollows and shadows formed in unidirectional flows (after Allen, 1984).

obstacle mark data from the sandur were plotted using the relationships of Karcz (1968), Larras (1963) and Breusers (1965) (Fig. 19, Table 1). The two latter equations overestimated the degree of scour found with each obstacle size (Fig. 19). This may be partially explained as these studies assumed a circular and cylindrical obstacle at 90° to a bed of uniform bed material (Larras, 1963; Breusers, 1965). More importantly, ice block obstacles being of lower density are likely to be displaced at high flow velocities preventing the development of horseshoe vortices.

Obstacle shape is also thought to influence the depth of scour, with square obstacles producing more scour than streamlined bodies of the same size (Karcz, 1968; Allen, 1984), because of increased forward flow separation produced by greater resistance to flow. Observations, however, showed that ice blocks were generally compact, being easily comminuted during transport. The importance of ice block shape for obstacle mark form is illustrated by the presence of two tails of sediment merging downstream into sandy dunes, downstream of a triangular ice block, observed resting on its apex (Fig. 20).

The effects of flow velocity and obstacle dimensions on obstacle shadow dimensions

Karcz (1968) and Allen (1984) suggested shadow formation behind an obstacle until flow velocities reach a certain threshold, when the flow separation boundary in the lee of the obstacle is destroyed by increasing turbulence. Such increases in turbulence result in an increased ability to remove material from the lee of the obstacle (Karcz, 1968; Allen, 1984). Of the 53 ice block obstacle marks examined on the sandur none exhibited scour hollows in its lee. It is likely that ice blocks would slide and roll downstream rather than remaining in position under the velocities required for lee side scour to occur. That increased turbulence, brought about by higher flow velocities, results in scour in the obstacle lee is supported by comparison with a large boulder of similar dimensions to grounded ice blocks (4 x 3 x 2 m) found adjacent to the area of ice block deposition (Fig. 21). The lee of this obstacle has been scoured out, suggesting that high flow velocities and considerable turbulence occurred at flow depths of 1·5 m. The material in the scour hollow is also finest near the obstacle and coarsens downstream, indicating a lessening degree of lee side turbulence away from the obstacle. Similar examples have been documented within high energy fluvial systems (Baker, 1973; Russell, in press).

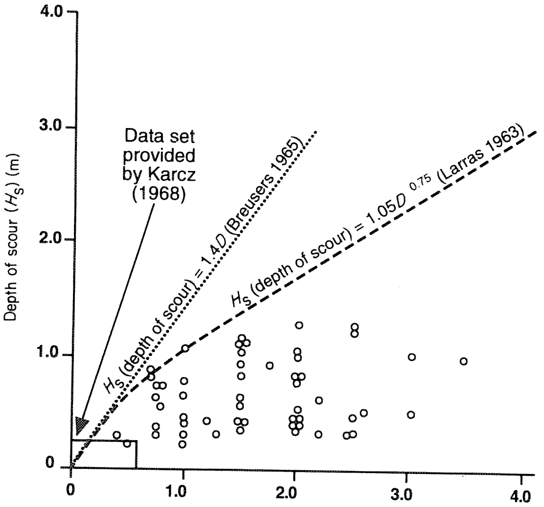


Fig. 19. Plot of maximum depth of scour below mean bed level against obstacle diameter. Previous relationships are plotted for comparison.

The nature of the obstacle shadow

Karcz (1968) suggested that the dimensions of the shadow depended on both obstacle size and sediment supply conditions, with larger obstacles resulting in the preservation of a larger tail during erosive flows, and sediment availability determining the size of tails within depositional conditions. Data collected on the sandur indicate a crude relationship between obstacle diameter and obstacle shadow height above mean bed level (Fig. 22).

Allen (1984) outlines various current crescent and shadow forms based upon the parameters of current strength, the size of sediment transported and the nature of the flow boundary, suggesting that these parameters determine the morphology and composition of the obstacle marks (Fig. 18). Of the seven combinations of obstacle mark morphology and composition only three are similar to those found in this field study (Fig. 18a,b,e). Field observations suggest that the distinction between the shadows of categories (a) and (b) is not clear cut. Two ice block obstacle marks were excavated in order to establish depths of erosion and deposition (obstacle marks A and B in Fig. 23). Three square-shaped pits were excavated into each hollow upstream of the obstacle mark, proximally within the shadow and distally within the shadow. The proximal pits were intended to indicate the nature of undisturbed substrate.

Fig. 20. A triangular shaped ice block with sandy tails illustrates the importance of ice block shape for obstacle mark morphology. Flow was from bottom right to top left. Rule is 1 m in length.

Fig. 21. Cluster bedform with proximal deposition and distal erosion around a large (4 × 3 × 2 m) boulder. Note the progessive fining of sediment towards the lee of the boulder. Flow was from left to right.

Shadow excavation was carried out to determine an erosional or depositional origin.

Obstacle marks A and B are formed on a gravel bar comprising repeated coarsening upward sequences of planar cross stratified gravel units separated by erosional contacts containing coarse grained lag material (Russell, 1991). A maximum of five planar cross stratified gravel units could be picked out from the pits excavated proximal to the obstacle marks (Fig. 23).

Coarse surface units in the shadow of obstacle mark A suggest shadow surface reworking. That erosional contacts within the shadow of obstacle mark A lie below the undisturbed bed level suggests an erosional origin for the ice block obstacle mark, with aerial waning stage reworking accounting for the coarse upper unit.

It is suggested that the top 0·6 m of the proximal section (B) is related to 1987 jökulhlaup flows as these sediments overlie finer grained sands and are in a zone

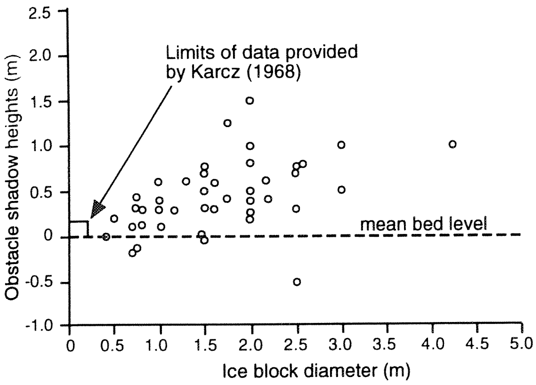


Fig. 22. Relationship between obstacle shadow height and obstacle diameter compared with the data set provided by Karcz (1968).

of net aggradation. The thin, coarsening upward, surface layer probably represents a lag deposit developed by waning stage winnowing of sediment. Thicker, poorly sorted, coarsening upward sequences found in distal sections may be contemporaneous with the proximal winnowed surficial unit. The poorly sorted nature of surface sediment in the obstacle shadow supports the idea of shadow deposition on the lee side of the tail pile to heights of 0·4 m above the surrounding undisturbed terrain simultaneously with proximal scour around grounded blocks. As such, localized scour was initiated before and during a general period of waning stage aerial bar surface erosion.

Sediment was preserved in the lee of both ice block obstacles examined. A coarse grained, poorly sorted layer of sediment on top of shadow B indicates the preferential deposition of material behind the obstacle. This situation is similar to (g) in Fig. 18 except for the fact that there is marked proximal and lateral erosion associated with examples in the field.

Other differences between predicted and actual morphologies are that the obstacle shadows in the field are less streamlined, exhibiting a mound-like appearance, and in many cases directed transverse to the flow direction. Obstacle marks developed in the coarsest sediment show the extent of the scour restricted to an ice block proximal location.

Erodibility of the substrate

The substrate proximal to obstacle marks A and B consists of loosely packed, openwork gravels presenting little resistance to erosion by horseshoe vortices on the stoss side of the ice block. Size frequency data for the coarsest clasts on, and immediately beneath, the surface were gathered and converted to weight frequency. Samples taken upstream of obstacle marks A and B and at another nine locations show generally coarser grained surface sediment (Fig. 24). Surface and subsurface samples taken both from the bottom of obstacle mark hollows and the proximal and distal portions of obstacle shadows show coarser grained material on the surface, as was also found in the undisturbed areas (Figs 24 and 25). This suggests that winnowing also takes place during localized proximal scour and after shadow deposition.

Depositional requirements for obstacle shadow ridges

For sediment to be deposited at a higher elevation than the surrounding bed in the obstacle lee, it must either be in suspension or in high saltation (Allen, 1984). Observations indicate deposition of finer grained sediment in the immediate wake of the obstacle but deposition of coarser grained, gravel–cobble sized material on the obstacle shadow ridge.

DISCUSSION AND CONCLUSIONS

Existing relations between flow conditions and obstacle mark size and morphology can be used to provide palaeoflow data both within present day proglacial river channels and even within the sedimentary record. The morphology and internal sedimentary characteristics of ice block obstacle marks, combined with spatial information about their distribution within river channels, may provide information regarding former water depths, velocities, flow directions and bedload transport conditions.

Flow directions

The use of obstacle marks in determining palaeoflow directions has been suggested by Gustavson (1974) and Allen (1984) and is demonstrated from the sedimentary record by Peabody (1947). Flow directions observed during flood flow were consistent with those indicated by the orientation and morphology of both scour hollows and obstacle shadows (Fig. 12). Variations between the morphology and orientation of individual obstacle marks occur where flow directions change markedly with stage (Fig. 12) and also where numerous obstacles can produce interference patterns (Karcz, 1968; Fig. 12). Flow directions

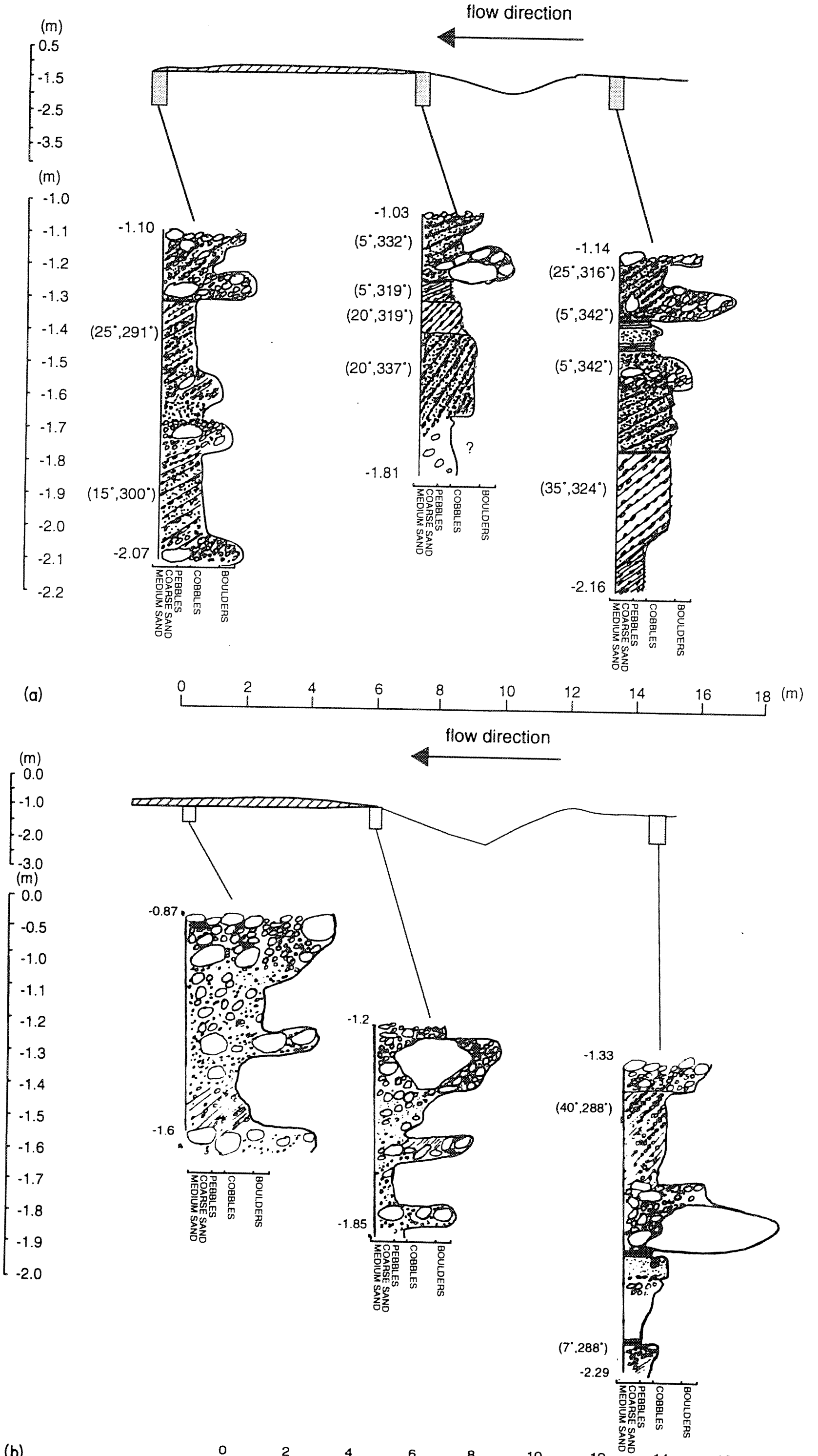


Fig. 23. Sedimentology of ice block obstacle mark A. The orientation and angle of dip are marked for each cross stratified unit. (b) Sedimentology of ice block obstacle mark B. This obstacle mark is also illustrated in plan view (Fig. 3) and in Fig. 11(a). The orientation and angle of dip are marked for each cross stratified unit.

Fig. 2
Samp

deter
used
the fa
and s

Wate

Palae
the se
water
scour
howe
their

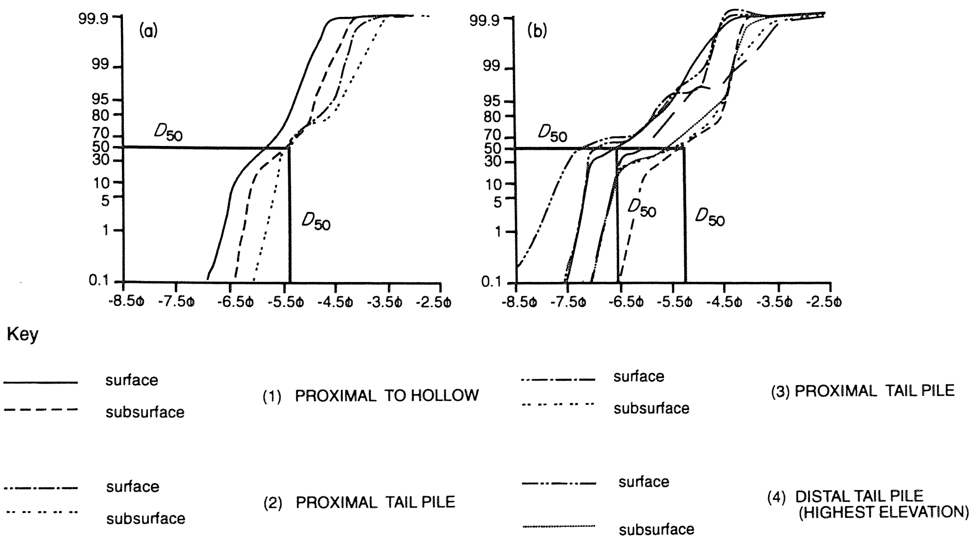


Fig. 24. Cumulative size frequency data for parts of ice block obstacle marks A and B (a, b, respectively).

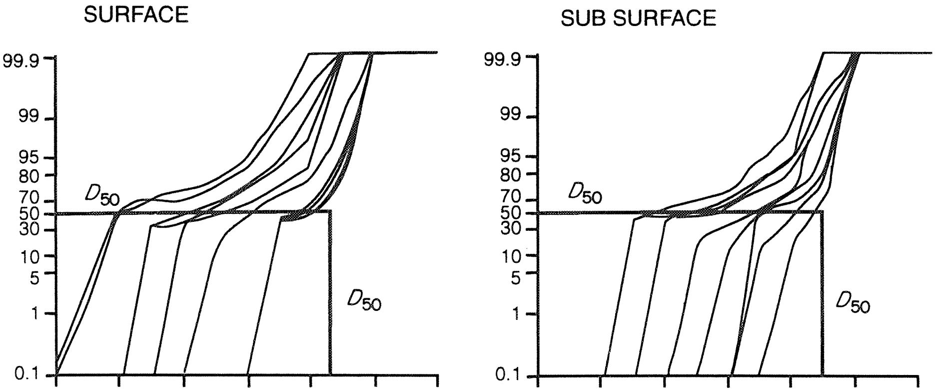


Fig. 25. Cumulative size frequency data for bar surfaces and immediate subsurfaces for lateral and lower bars on the sandur. Samples are not associated with ice blocks.

determined from obstacle mark morphology were used successfully to chart flow direction changes on the falling limb of the 1987 jökulhlaup on the delta and sandur plain.

Water depths

Palaeoflow depths are more difficult to determine from the sedimentary record if the obstacles are denser than water, as the range of stages and velocities producing scour would be indeterminable. Pure ice blocks will, however, float in water equal in depth to 0·9 times their diameter and will move by traction in water depths of 0·5–0·6 times the ice block diameter. Actual grounding depths may depend upon ice block sediment content, water velocities, local bed roughness and the amount of bedload. Since obstacle size is related to flow depth on ice block grounding, estimations can be made of the dimensions of the ice block from both the height of the shadow above the sandur and the detailed sedimentology of the obstacle mark. Obstacle mark sedimentology may indicate former ice block dimensions and grounding depths. Ice of a different density and shape, such as seasonal river ice, may ground in water depths less or greater than 0·5–0·6 times the ice block diameter. Tabular river ice is unlikely to roll across the bed of the river like the glacier-derived ice blocks observed in this study. Clues as to the origin of the ice blocks can be provided by the presence or absence of distinctive meltout deposits (Fig. 10c).

Despite potential (unquantified) errors due to differences in bed roughness, flow velocity and bed mobility, a maximum flow depth for grounding may be given by 0·5–0·9 times the diameter of the ice block, estimated from the depth of scour, the height of the obstacle shadow or the extent of ice block meltout sediments. The minimum flow depth may be determined using the height of the obstacle shadow above the mean bed level.

Bedload conditions

The sedimentology of obstacle shadows provides information about sediment transport conditions during the waning stages of a jökulhlaup. Obstacle shadows can be either erosional or depositional. The character of sedimentary structures and particle size distributions found within depositional shadows may indicate the capacity and character of sediment transport during, and soon after, ice block grounding. The internal composition of the shadow indicates the capacity of the flow to transport sediment into the lee of obstacles. Shadow sediments may be coarser than surrounding material due to preferential deposition of material eroded from the proximal and lateral scour hollows.

Sedimentary structures and preservation potential of obstacle marks

All the bedforms discussed in this study will either be destroyed by erosion during the rising limb of the next jökulhlaup or will be buried and preserved. In many cases the sedimentary record of jökulhlaups constitutes the last high magnitude flow event before a proglacial outwash system is abandoned on deglaciation (Baker, 1973; Elfström, 1983, 1985). Many proglacial outwash deposits may contain ice block grounding structures related to regular jökulhlaups.

Ice block grounding structures as initiators of channel change

Ice blocks grounded within the distal portion of the sandur initiated waning stage bar dissection. Proximal and lateral erosion around ice blocks has, in places, extended for distances beyond the ice block, forming chute channels (Figs 11b and 12). These chutes captured waning stage flows, resulting in further incision and the subsequent depostion of lobate or deltaic deposits beyond the dissected bar front (Fig. 11b). As ice blocks are grounded on bar crests they are in an ideal position to initiate bed scour with consequent bar incision.

The input of ice blocks is likely to vary according to the magnitude of an event and the stability of nearby ice fronts; the degree of bar incision may also vary greatly between events. The timing of the jökulhlaup within the melt season may also influence ice margin stability and the potential for jökulhlaups to transport ice blocks.

Wider implications

This study illustrates the importance of glacier ice grounding and subsequent scour for the morphology and sedimentology of proximal proglacial fluvial outwash. Ice block obstacle marks, if preserved in section or on former channel surfaces, may prove a valuable tool for estimating palaeoflow conditions during such high magnitude flood events. In particular, palaeoflow depths and velocities ascertained from these features may be extremely useful for the reconstruction of flow magnitude and frequency in former glacier outwash systems. Further study is needed, however, to examine the relationship between ice block obstacle mark form, flow conditions and substrate conditions.

ACKNOWLEDGMENTS

This work was carried out while the author was in receipt of an NERC research studentship within the Department of Geography at the University of Aberdeen. I thank Professor C. M. Clapperton, Dr J. K. Maizels and Professor I. Reid for constructive comments on previous versions of this manuscript. Carmen de Jong, Liz Elvidge, Ric Gard, Judith Maizels and John Sinclair provided field assistance in Greenland, often under arduous conditions. Thanks also go to Debbie Millard within the School of Geography at Kingston University for cartographic work.

REFERENCES

Allen, J.R.L. (1984) *Sedimentary Structures: Their Character and Physical Basis*, Vol. 2. Elsevier, Amsterdam.

Baker, V.R. (1973) Paleohydrology and sedimentology of lake Missoula flooding in Eastern Washington. *Spec. Pap. geol. Soc. of Am.*, **144**.

BRADLEY, J.B. & MCCUTCHEON, S.C. (1987) Influence of large suspended sediment concentrations in rivers. In: *Sediment Transport in Gravel Bed Rivers* (Ed. by C. R. Thorne, J. C. Bathurst & R. D. Hey). Wiley, Chichester.

BREUSERS, H.N.C. (1965) Scour around drilling platforms. *Bull. int. Ass. Hydraulic Res.*, **19**.

CARSTENS, T. & SHARMA, H.R. (1975) Local scour around large objects. In: *Proc. int. Assoc. Hydraulic Research*, pp. 251–262. I.A.H.R.

COLLINSON, J.D. (1971) Some effects of ice on a river bed. *J. sedim. Petrol.*, **41**, 557–564.

ELFSTRÖM, A. (1987) Large boulder deposits and catastrophic floods. *Geog. Annlr*, **69A**, 101–121.

FAHNESTOCK, R.K. & BRADLEY, W.C. (1973) Knik and Matanuska rivers, Alaska: a contrast in braiding. In: *Fluvial Geomorphology* (Ed. by M. Morisawa), pp. 220–250. Allen & Unwin.

GORDON, J.E. (1986) Correspondence concerning glacial lake drainage near Søndre Strømfjord, West Greenland. *J. Glaciol.*, **32**, 304.

GUSTAVSON, T.C. (1974) Sedimentation on gravel outwash fans Malaspina glacial foreland, Alaska. *J. sedim. Petrol.*, **44**, 374–389.

KARCZ, I. (1968) Fluviatile obstacle marks from the wadis of the Negev. *J. sedim. Petrol.*, **38**, 1060–1072.

KRAINER, K. & POSCHER, G. (1990) Ice-rich, redeposited diamicton blocks and associated structures in Quaternary outwash sediments of the Inn valley near Innsbruck, Austria. *Geograf. Annlr*, **72A**, 249–255.

LARRAS, J. (1963) *Ann. Ponts Chauss.*, **133**, 411–424.

MAIZELS, J.K. (1977) Experiments on the origin of kettle-holes. *J. Glaciol.*, **18**, 291–303.

PEABODY, F.E. (1947) Current crescents in the Triassic Moenkopi formation. *J. sedim. Petrol.*, **17**, 73–76.

RICHARDSON, P.D. (1968) The generation of scour marks near obstacles. *J. sedim. Petrol.*, **38**, 965–970.

RUSSELL, A.J. (1989) A comparison of two recent jökulhlaups from an ice-dammed lake, Søndre Strømfjord, West Greenland. *J. Glaciol.*, **35**, 157–162.

RUSSELL, A.J. (1991) *The geomorphological and sedimentological effects of jökulhlaups. PhD thesis*, University of Aberdeen.

RUSSELL, A.J. (in press) Subglacial jökulhlaup deposition, Jotunheimen Norway. *Sediment. Geol.*

RUSSELL, A.J. & DE JONG, C. (1989) Lake drainage mechanisms for the ice-dammed Oberer Russellsee, Søndre Strømfjord, West Greenland. *Z. Gletscherkunde Glazialgeol.*, **24**, 143–147.

SCHOLZ, H., SCHREINER, B. & FUNK, H. (1988) Der einfluss von Gletscherlaufen auf die schmelzwasserablagerungen des Russell-Gletschers bei Söndre Strömfjord (West-Grönland). *Z. Gletscherkunde Glazialgeol.*, **24**, S55–74.

SENGUPTA, S. (1966) Studies on orientation and imbrication of pebbles with respect to cross-stratification. *J. sedim. Petrol.*, **36**, 362–369.

SHEN, H.W., SCHNEIDER, V.R. & KARAKI, S. (1969) Local scour around bridge piers. *J. hydrol. Div. Am. Soc. cn. Engrs*, **95**, 1919–1940.

SUGDEN, D.E., CLAPPERTON, C.M. & KNIGHT, P.G. (1985) A jökulhlaup near Søndre Strømfjord, West Greenland, and some effects on the Ice sheet margin. *J. Glaciol.*, **31**, 366–368.

(Manuscript received 11 June 1992; revision accepted 9 June 1993)